EXECUTIVE SUMMARY

The Mir Environmental Effects Package (MEEP) was deployed on the Mir Station by STS-76 and retrieved, following 18 months in space, by STS 86. This payload, managed by Langley Research Center, included the Orbital Debris Collector (ODC) that was designed and built at the Johnson Space Center. The objective of ODC was to capture and return analyzable residues of the man-made and natural particulate environment in low-Earth orbit for a detailed assessment of its compositional make up and potential origins.

ODC exposed highly porous, low-density (0.02 g/cm^3) SiO_2 aerogel as the basic collector medium. Based on laboratory impact simulations by a number of groups, this material is ideally suited to gently decelerate and capture hypervelocity particles, as demonstrated by unmolten remnants of silicate and aluminum projectiles fired at velocities as high as 7 km/s. This capability offers a significant improvement over traditional, comparatively dense collector media, including those exposed on the Long Duration Exposure Facility (LDEF). The latter resulted in pervasive melting, if not complete vaporization of many impactors, leaving little or no residue for analysis. The expectation was that ODC would return a larger number and wider diversity of particles than all previous collection efforts in low-Earth orbit.

Even cursory inspection of the returned ODC collectors revealed a surprising variety of impact features. The major class of slender, carrot-shaped penetration *tracks* was as expected from laboratory impacts, including the presence of trapped projectile residue at their termini. The typical length (L) to diameter (D) ratio of these tracks is L/D > 20, and as high as 40. A second class of features is rather shallow, with L/D ranging from 0.5 to 5. For the most part, these shallow *pits* did not contain measurable residues, and have no experimental analog at velocities as high as 7 km/s. Impact features exhibiting morphologies intermediate between these two extremes suggest that there is a morphological continuum. We suggest this continuum to be an evolutionary sequence related to impact velocity. The deep tracks reflect modest encounter velocities, consistent with unmolten penetrators at the terminus, while the shallow pits form above some threshold velocity that resulted in pervasive vapor production and thus, shallow penetration, combined with substantial, if not complete, loss of the impactor. Apparently, the utility of aerogel has a velocity dependent limit beyond which complete vaporization of the impactor may not be prevented. This threshold velocity for vaporization is unknown for aerogel but it is undoubtedly higher than for non-porous materials, rendering aerogel the vastly superior collector medium in low-Earth orbit.

A third group of impact features in the ODC aerogel is related to low-velocity impacts of co-orbiting flakes and liquid droplets, all human waste products and the result of waste-water dumps. These features are either very irregular in shape and shallow (L/D < 0.5), associated with pervasively crushed aerogel and copious amounts of particulate impactor material, or they are very regular, round depressions of L/D = 1 to 2. The latter possess a thin petri-dish shaped deposit in their bottoms that displays highly concentric qualities (*e.g.*, color shades) suggesting in-situ formation by evaporation from a liquid. The encounter with liquid droplets was also reported from other MEEP experiments.

ODC exposed two identical trays, Tray 1 nominally pointing into the ram direction, Tray 2 in the opposite direction. The macroscopic survey of all impact features > 3 mm reveals Tray 1 to be dominated by low-velocity waste impacts, ~ 73%, as opposed to 25% on Tray 2. Pits make up

~ 16% on Tray 1 and 29% on Tray 2, and tracks compose the remaining 11% and 45% on Tray 1 and 2, respectively. The high-track abundance on Tray 2 is affected by discrete clusters of tracks, all of the same orientation (azimuth and inclination), suggesting that they resulted from a swarm of secondary projectiles from a local, primary impact. Detailed optical analysis of aerogel surfaces is time consuming and, to date, is limited to features > 500 µm and to 30% of each tray surface. The distribution of track lengths on both trays is nearly identical. The radiants from which track-forming particles originated are random on both trays, except for the clustered impactors on Tray 2. The ratio of track length to residue size scatters widely, akin to experimental results, and attests to highly idiosyncratic penetration and mass-loss processes for individual aerogel impacts. Therefore, it is not possible to extract meaningful data regarding initial impactor mass from aerogels. As a consequence, particle-flux measurements derived from ODC are rather qualitative, although of the same order-of-magnitude than those derived from LDEF.

Harvesting and compositional analysis of individual particles is tedious and significant effort went into the development of suitable techniques, minimizing the inadvertent loss of particles typically 10 µm or smaller. The compositional analyses using SEM-EDS methods concentrated on a survey-type inventory of diverse particle types and associated impact features. Accordingly, all flake and droplet features typically contain the biogenic elements K, Na, Cl, and P and must be assigned to human-waste products. All highly transparent pit features analyzed to date contain no detectable impactor residue; the latter is presumably vaporized, attesting to the high-velocity origin of these features. The majority of the carrot-shaped tracks contain analyzable residue. Among man-made particles we detected metallic Al, stainless steel, soldering compounds, and paint flakes. The swarm event is apparently due to some natural impactor, containing Fe, Mg, and Ca, that must have fragmented upon impact with a neighboring structure on Mir. One cosmic-dust particle was embedded in epoxy, microtomed, and investigated with TEM methods, the first unmolten, natural particle ever to be retrieved from low-Earth orbit for such detailed textural and mineralogical studies.

In summary, the optical analysis of the Mir collectors is complete, as is the survey type assessment of man-made or natural classes of particles. Although ODC observations suggest that the utility of aerogel for the capture of hypervelocity particles may be velocity limited, its performance is vastly superior to traditional, non-porous media. Hundreds of impactor residues were returned by ODC. Future ODC efforts will concentrate on the compositional analysis of a statistically significant fraction of these particles and an improved assessment of their origins.